

Active Combustion Control

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Outline

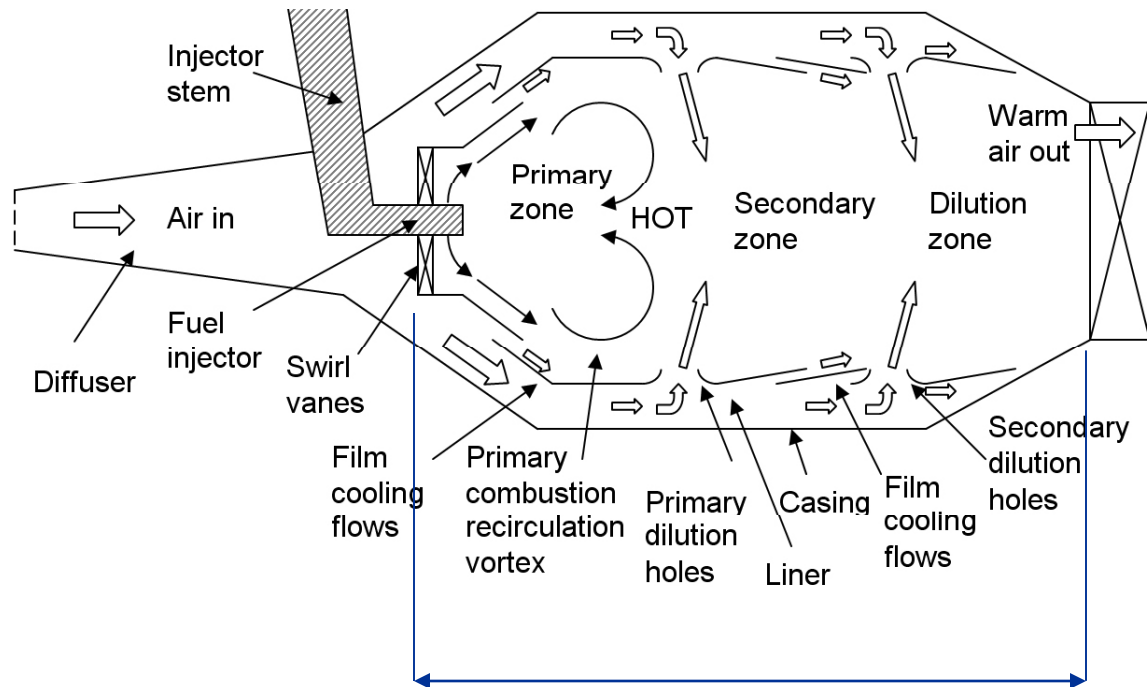
- Turbine Issue Being Addressed
 - Combustors 101
- Cleaner Emissions
 - Lean Burn Technology
 - RQL Technology Rich Burn, Quick Mix, Lean Burn (RQL)
- Thermo-Acoustic Instability
- Thermo-Acoustic Instability Reduction
- Active Combustion Control
 - Strategy
 - Challenge



Outline

- Sensor Research
- Fuel Flow Modulator Research
- Active Combustion Control Loop
- Summary
- Questions

Combustors 101



The length of conventional combustors is dictated by:

- Residence time required to evaporate the fuel,
- Ensure appropriate mixing, and
- Complete reactions

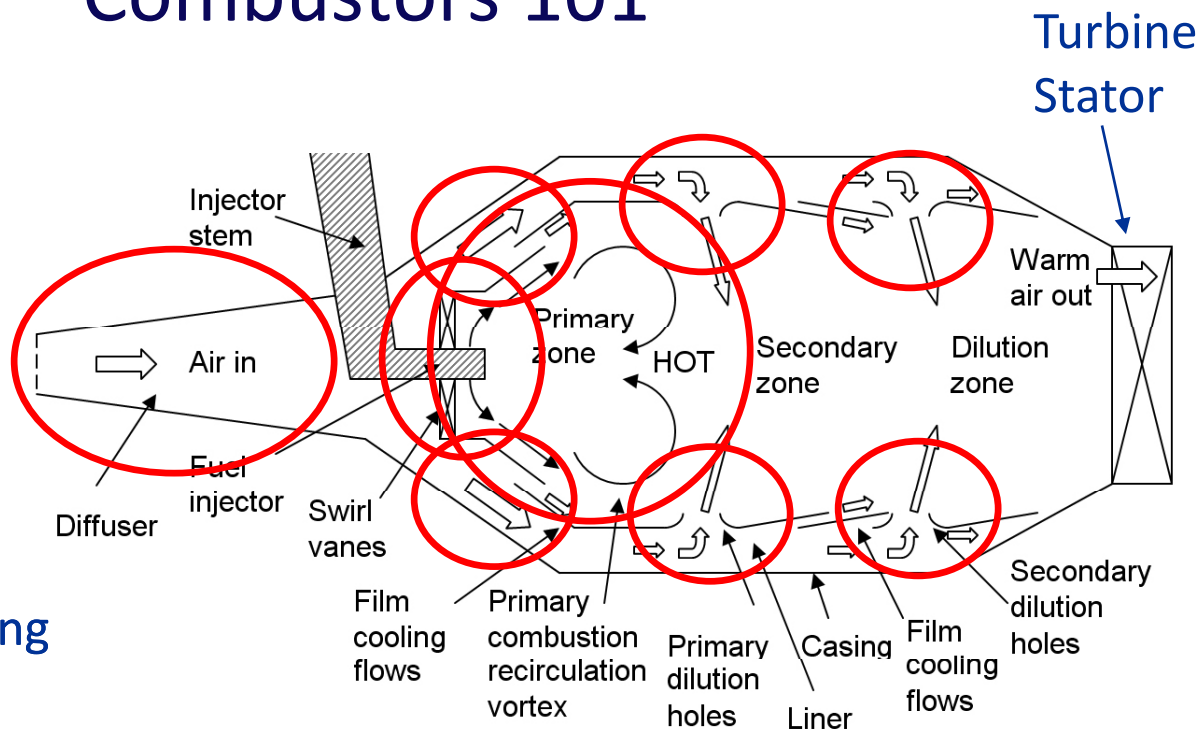
Combustors 101

Diffuser slows down flow speed to reduce Rayleigh loss

Fuel-nozzle turbulence speeds up atomization by breaking up liquid into droplets.

Liner film-cooling decouples thermal loading from pressure casing.

Swirling flow forms recirculating vortex to provide flame-holding.



Primary dilution holes provides dilution and vortex anchor.

Secondary dilution holes add more air to lower exit temperature.



Cleaner Emissions

International Civil Aviation Organization (ICAO)

Committee on Aviation Environmental Protection (CAEP)

To formulate policies, standards, and practices
related to aircraft noise and emissions.

*Much of the international focus has been on the reduction of NO_x.

Produced when air passes through high temperature/high pressure
combustion.

*NO_x reduction technologies include:

- Increase bypass ratio
- Lean burn technology
- Rich Burn, Quick Mix, Lean Burn (RQL) technology

*Neil Dickson, "Local Air Quality and ICAO Engine
Emissions Standards," ICAO Air Transport Bureau, 2014.



Lean Burn Technology

- Excess air is introduced into the engine along with the fuel.
 - Premix air and fuel upstream of the combustor.
 - Excess air reduces combustion temperature and this reduces the amount of NO_x produced.
 - Results in excess oxygen available. Therefore, combustion process is more efficient and more power is produced from the same amount of fuel.
- A mixture closer to stoichiometric can produce knocking and higher NO_x emissions
- Leaner mixtures may not combust reliably and cause misfiring.



RQL Technology

- Premise that primary zone operates most effectively with a rich mixture. This zone will incorporate a rich-burn condition ($>$ stoichiometric).
 - Rich burn condition minimizes the production of NO_x due to low temperatures and low population of oxygen.
 - Additional oxygen is needed to oxidize the high concentrations of carbon monoxide and hydrogen
- A substantial amount of air is injected through the wall to mix with the primary zone effluent and create a lean-burn condition.
 - Lean burn effluent exiting the combustor.



Thermo-Acoustic Instabilities

- Result of fluctuating heat release coupling with combustion chamber acoustics.
 - Growth of pressure fluctuation amplitudes can be detected
 - Pressure fluctuation frequency may be approximate to combustor acoustic resonant frequency.
 - *Exact mechanism is not well understood and different hypotheses exist.

*George Kopasakis, "Systems Characterization of Combustor Instabilities with Controls Design Emphasis," AIAA 2004-638, Jan, 2004.



Thermo-Acoustic Instability Reduction

1. Smart Combustor Design

- Passive control of instability
 - Redesign of combustor geometry
 - Shorten can,
 - Lengthen can,
 - Add baffles,
 - ...
 - Preferred and readily acceptable solution

2. Modulate airflow for out-of-phase cancellation

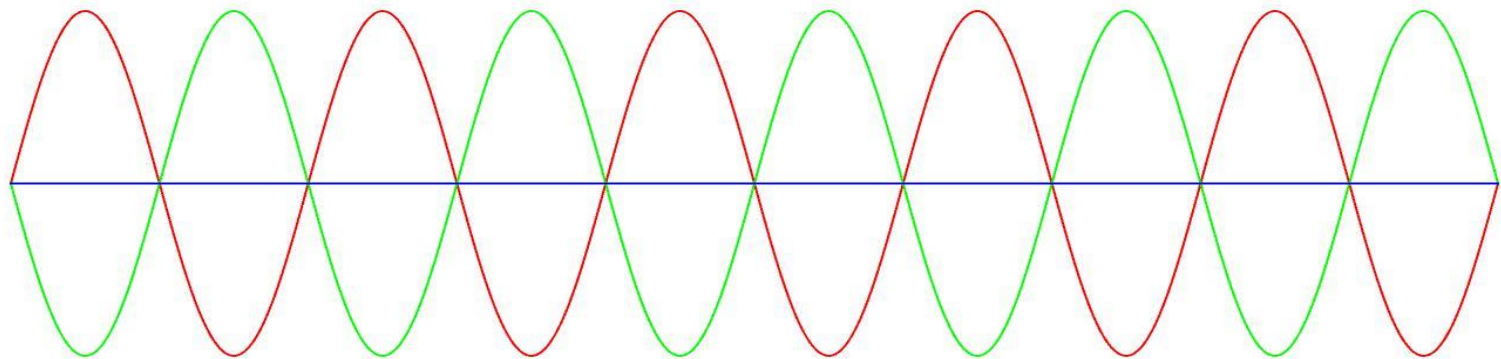
- High-pressure, -temperature, and –mass flow air.
- May adversely affect compressor balance.

3. Modulate fuel for out-of-phase cancellation

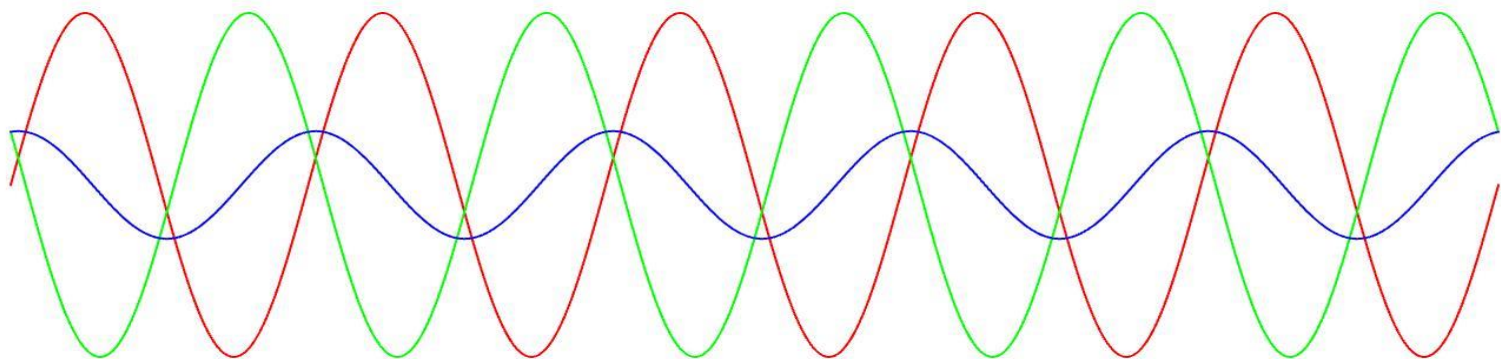
- Requires low-actuation power



Active Combustion Control Strategy

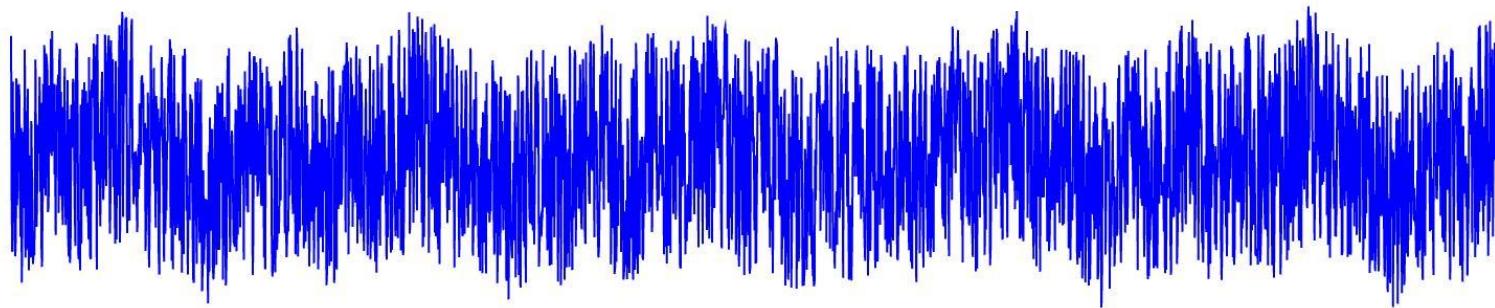


Instability
Out-of-phase
Resultant





Active Combustion Control Challenge



Very low signal to noise ratio



Combustor Dynamic Control Challenges

- Combustor
 - Test rig configuration
 - Fluid dynamic sensitivity
 - Staging flexibility
 - Fuel sensitivity
 - Thermo-acoustics
 - Part-load operability
- Sensing
 - Sensible phenomenon
 - Sensor
 - Sensor survival
- Control
 - Control Design Model
 - Noise rejection
 - Phase matching
- Actuation
 - Response speed
 - Size

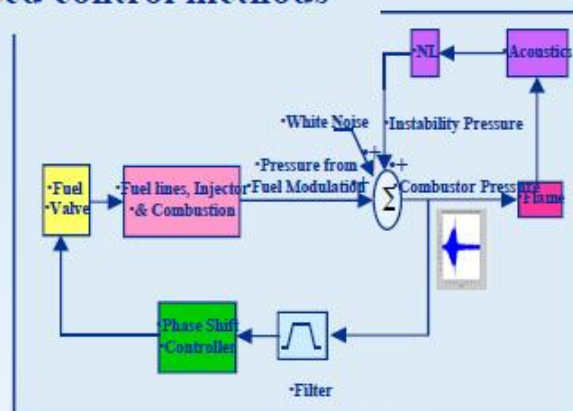


Previous Accomplishments

- Georgia Tech Modulator
- S1D_Matlab Simulation

Active Combustion Instability Control Via Fuel Modulation

Advanced control methods



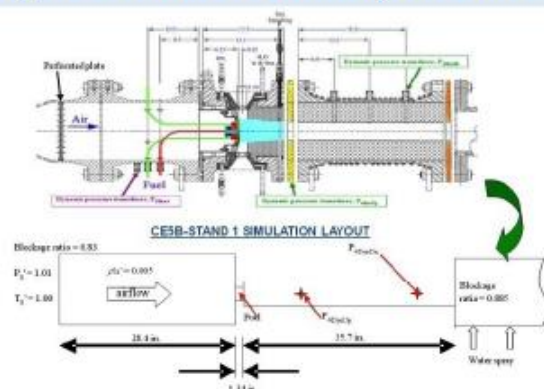
High-frequency fuel delivery system and models



High-temperature sensors and electronics



Physics-based instability models

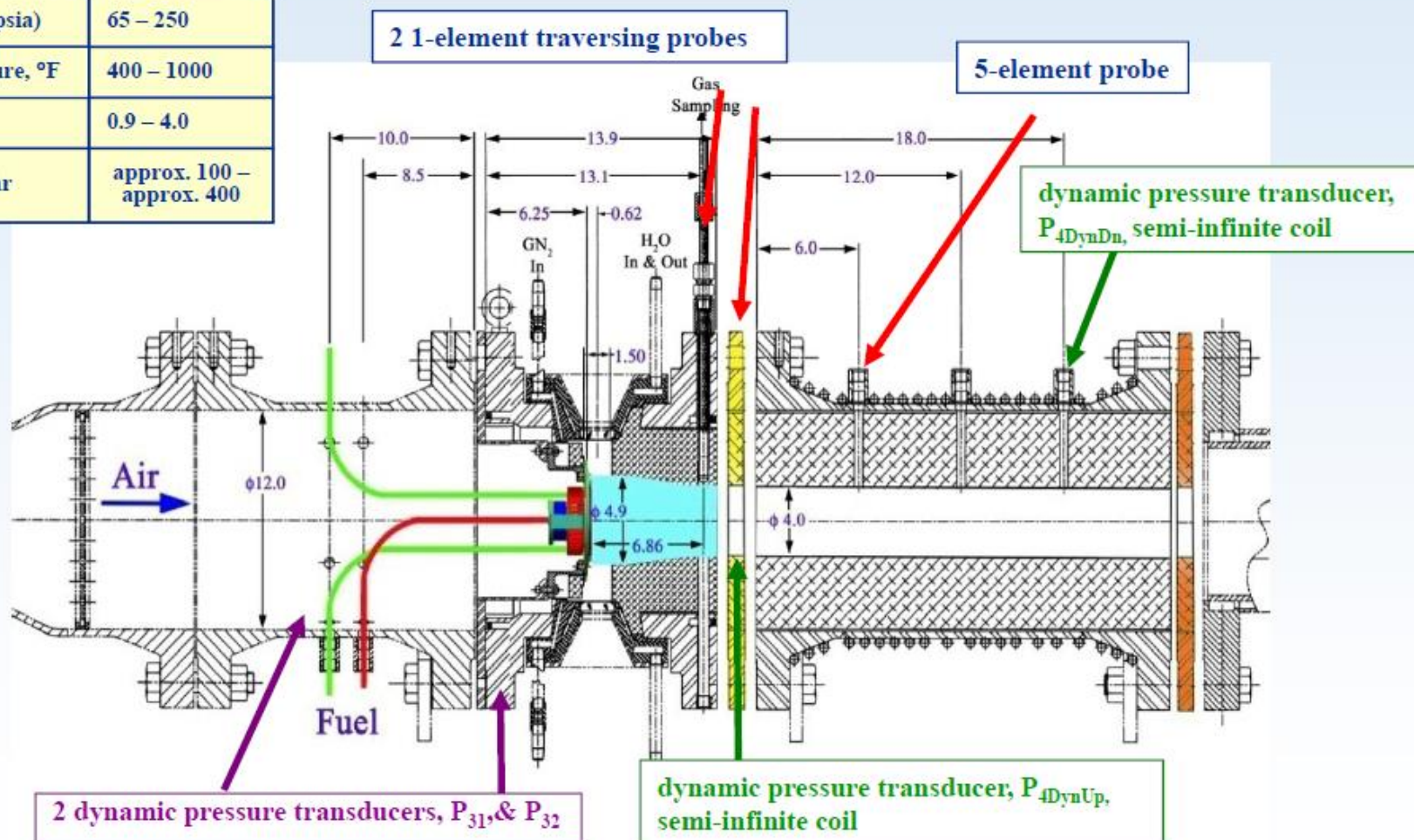


Realistic combustors, rigs for research

Low Emissions Combustor Prototype with Observed Instability, as installed in NASA CE5B-Stand 1

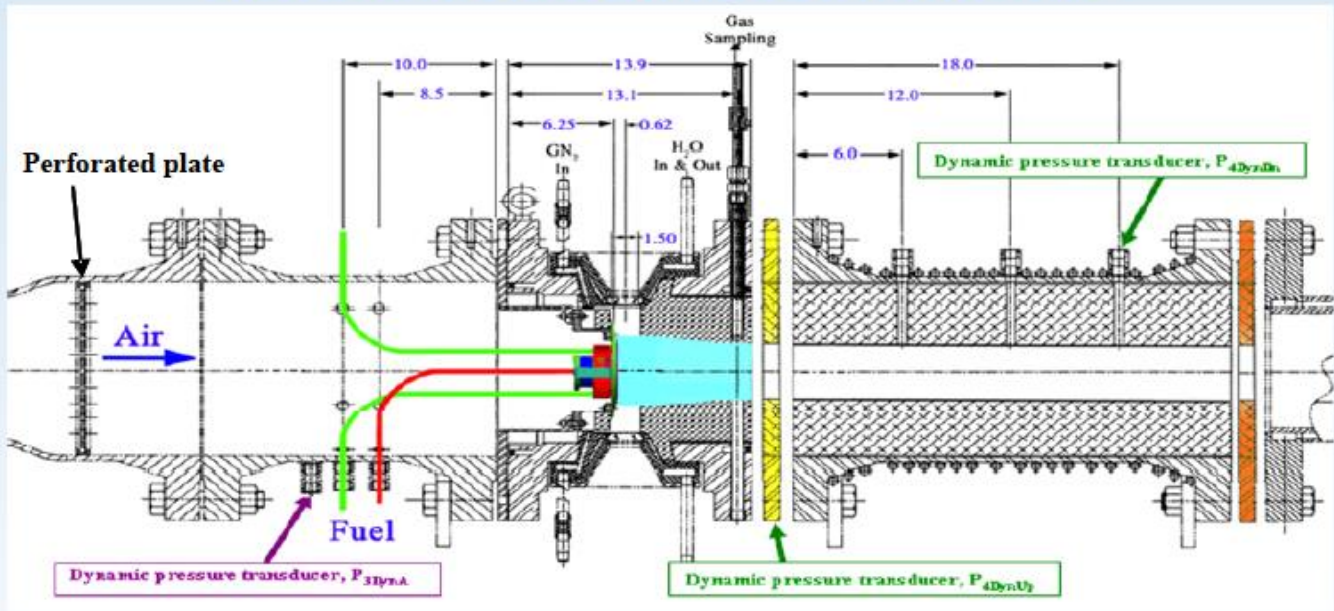
Range of Combustor Operating Conditions

Inlet Pressure (psia)	65 – 250
Inlet Temperature, °F	400 – 1000
Air Flow, lb _m /s	0.9 – 4.0
Fuel Flow, lb _m /hr	approx. 100 – approx. 400

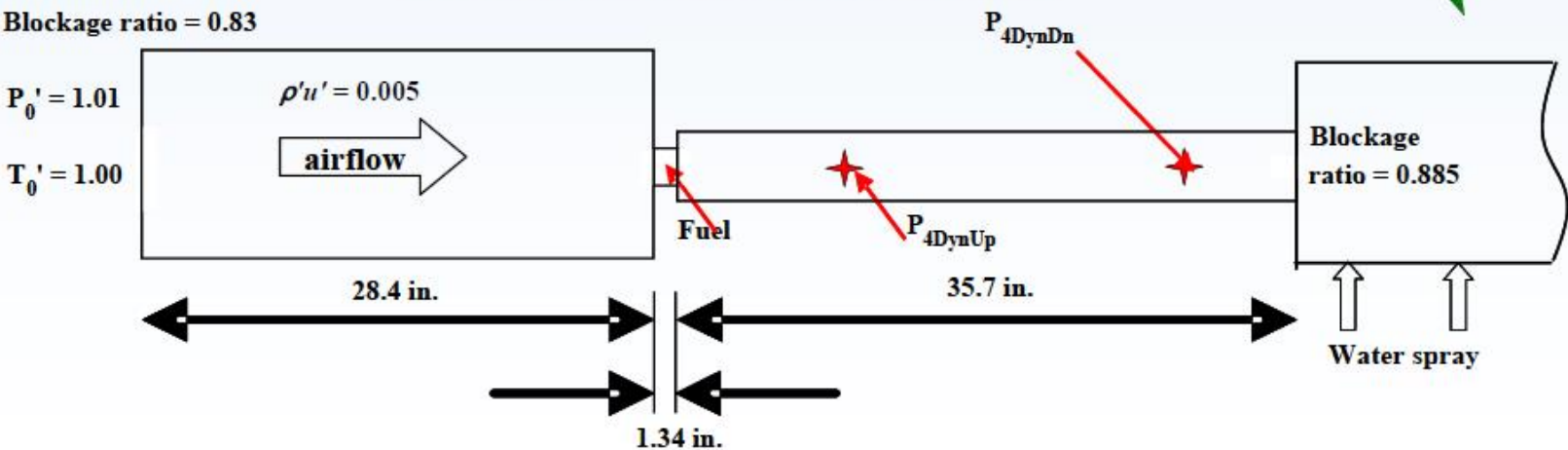




E. Closed-Loop Combustor Data for Development of Combustion Control Simulations



CE5B-STAND 1 SIMULATION LAYOUT





Active Combustion Control, Combustion Dynamic Model Development

PROBLEM: Lean direct injection combustors are susceptible to thermal-acoustic instabilities that can limit the performance envelope of a turbine engine.

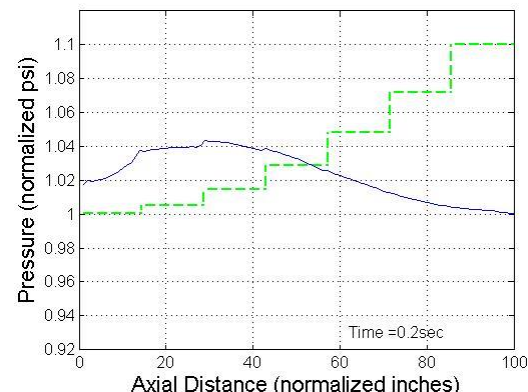
OBJECTIVE: Develop control laws to modulate fuel-flow into the combustor to mitigate growth of thermal-acoustic instabilities.

APPROACH: Develop a software tool to computationally predict an instability and then mitigate the instability using feedback control laws. First step involved translating legacy combustor simulation code to a format suitable for controls development. Second step is to apply closed loop control laws to the simulation. Third step is to apply control laws to a fuel modulator and combustor.

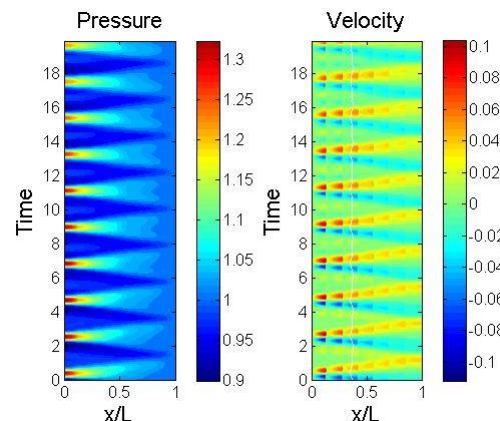
SIGNIFICANCE: A computational platform that can readily be interfaced with a feedback controller would streamline control law development prior to running combustion experiments. Previous code is very impressive and fast; however, that version of the software is also difficult to modify the process and interface it with modern control design tools. The process value is increased by reformatting the code to run in a simulation that can also readily accept control laws. Furthermore, while reformatting the code, considerations can be incorporated to streamline potential modifications when efforts change to entertain a unique combustor or design changes.

PROGRESS TO DATE:

Acoustic validation of MatLab based code. Simulation reproduced acoustic validation calculations as published by Paxson AIAA 2000-0313.



The above illustration is the final pressure profile after 40 simulation seconds. Green trace illustrates the contour of the simulated acoustic pipe with normalized diameter. Blue trace is final normalized pressure distribution. This illustration is regularly updated during simulation to see wave development.



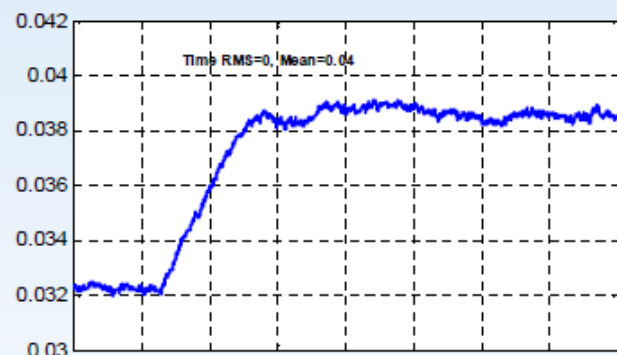
Pressure and airflow velocity profiles for simulation time spanning 20 simulation seconds. Periodic wave pattern can be identified in these illustrations. These results match simulation results published by Paxson.



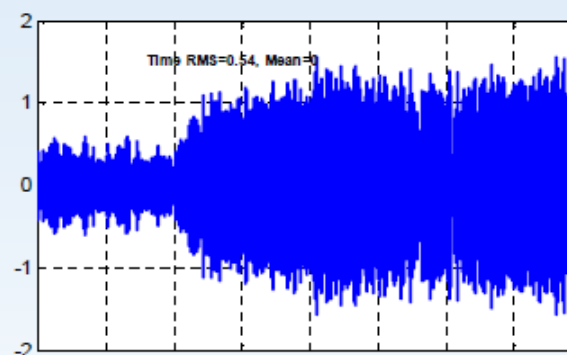
B. Demonstration of Combustion Instability Control

Adaptive Sliding Phasor Averaged Control (ASPAC) able to prevent instability growth

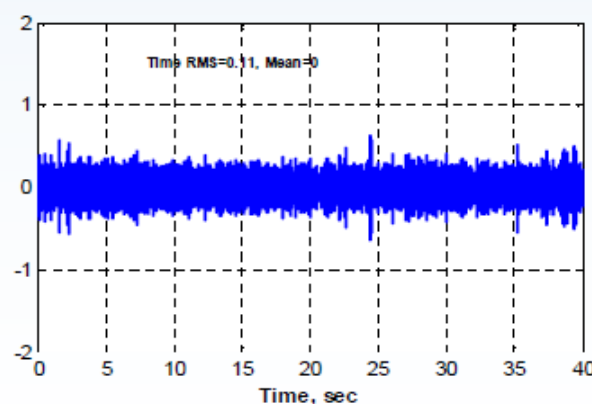
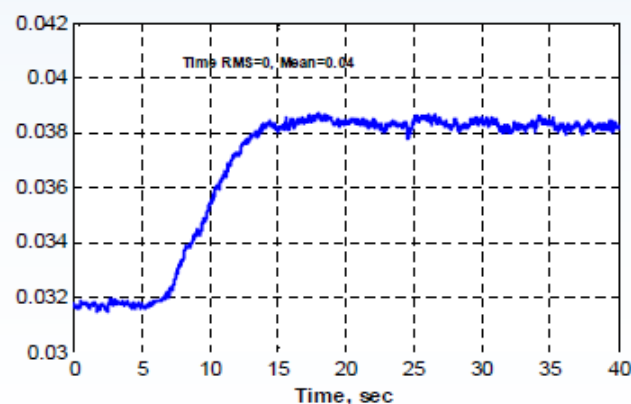
Fuel/air ratio



Filtered Combustor Pressure

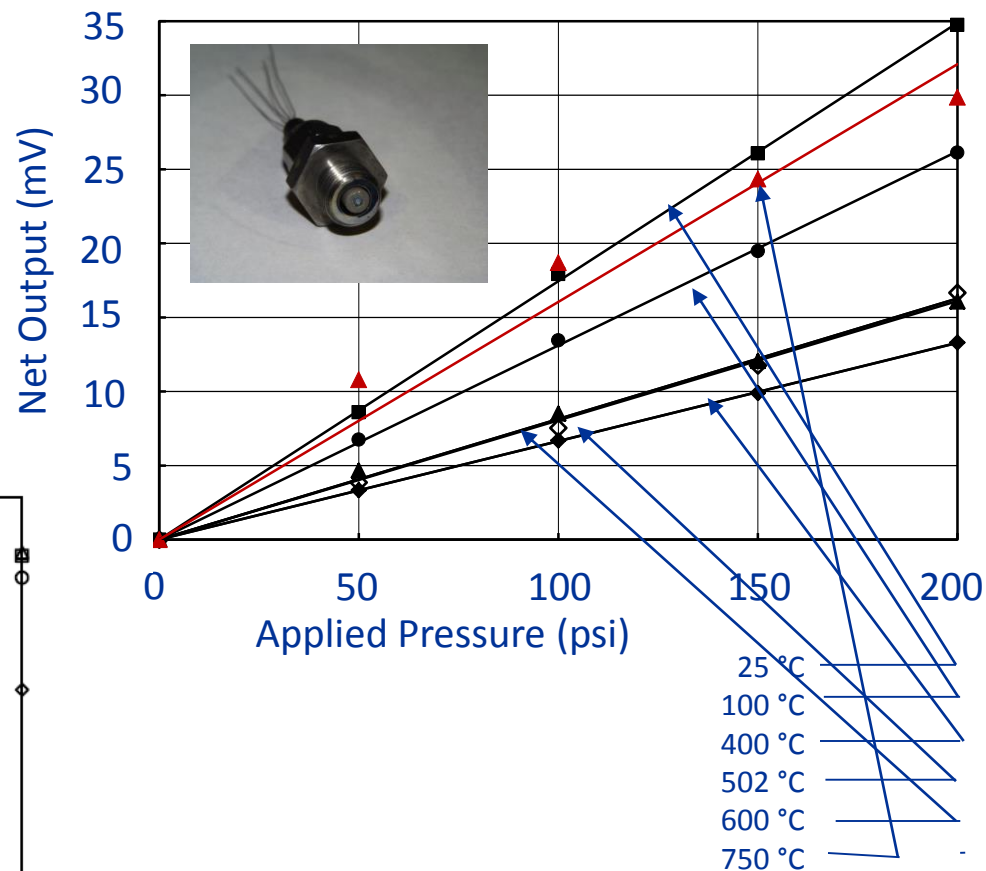
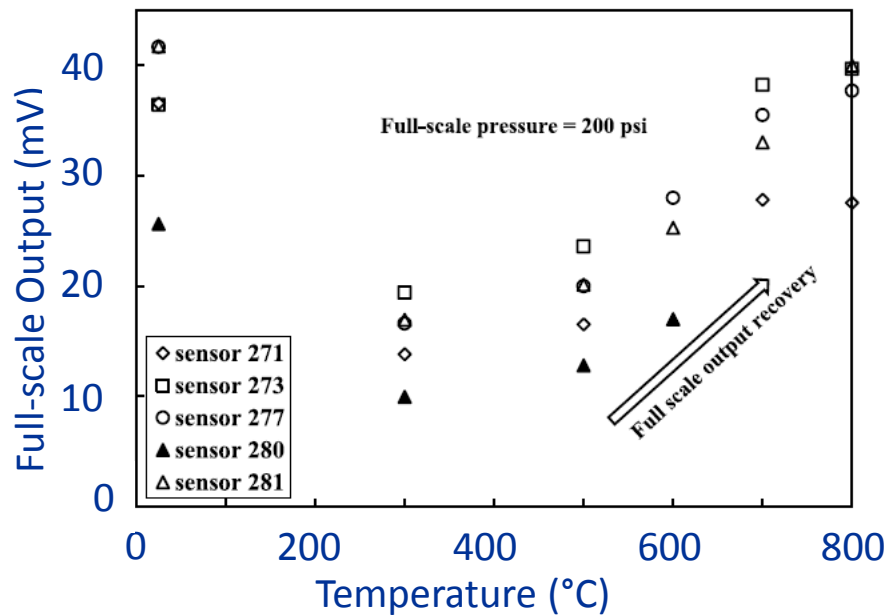


Controller off



Controller on

Sensing



Okojie, R., S., Lukco, D., Nguyen, V., and Savrun, E., "4H-SiC Piezoresistive Pressure Sensors at 800 °C with Observed Sensitivity Recovery," IEEE Electron Device Letters, Vol. 36, No. 2, February 2015.

NASA GRC Fuel Modulators

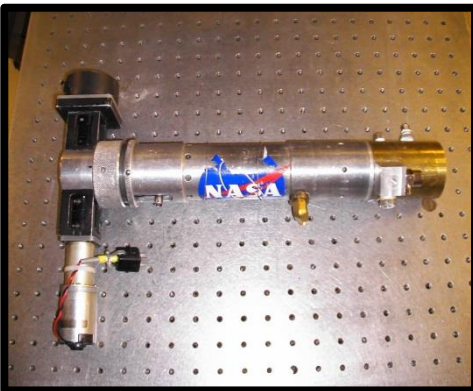
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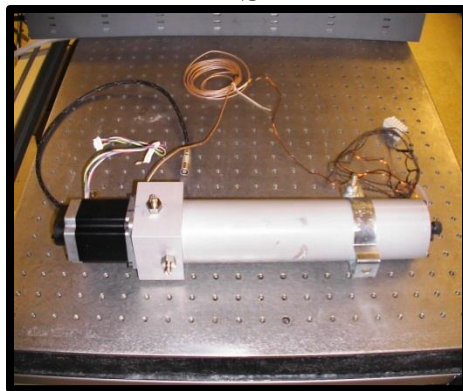
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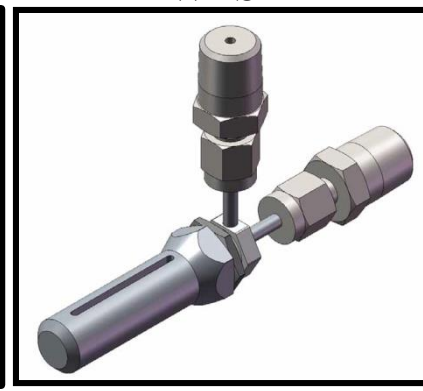
AST



JASC



WASK



Magneto-strictive
Exterior Installation
Design Point: FN=110
FN Range: 20 to 110

Magneto-strictive
Exterior Installation
Design Point: FN=5
FN Range: 3 to 8

Translating-Rotary Flute
w/stationary flow port
Exterior Installation
Design Point: FN=4
FN Range: 3 to 5

Piezoelectric
Interior Installation
Design Point: FN=4
FN Range: 1 to 8

Envelope: 12"x18"x2"
Weight: 20 lbs

Envelope: 4"x18"x4"
Weight: 10 lbs

Envelope: 2.6"x5.6"x2.6"
Weight: 3.5 lbs

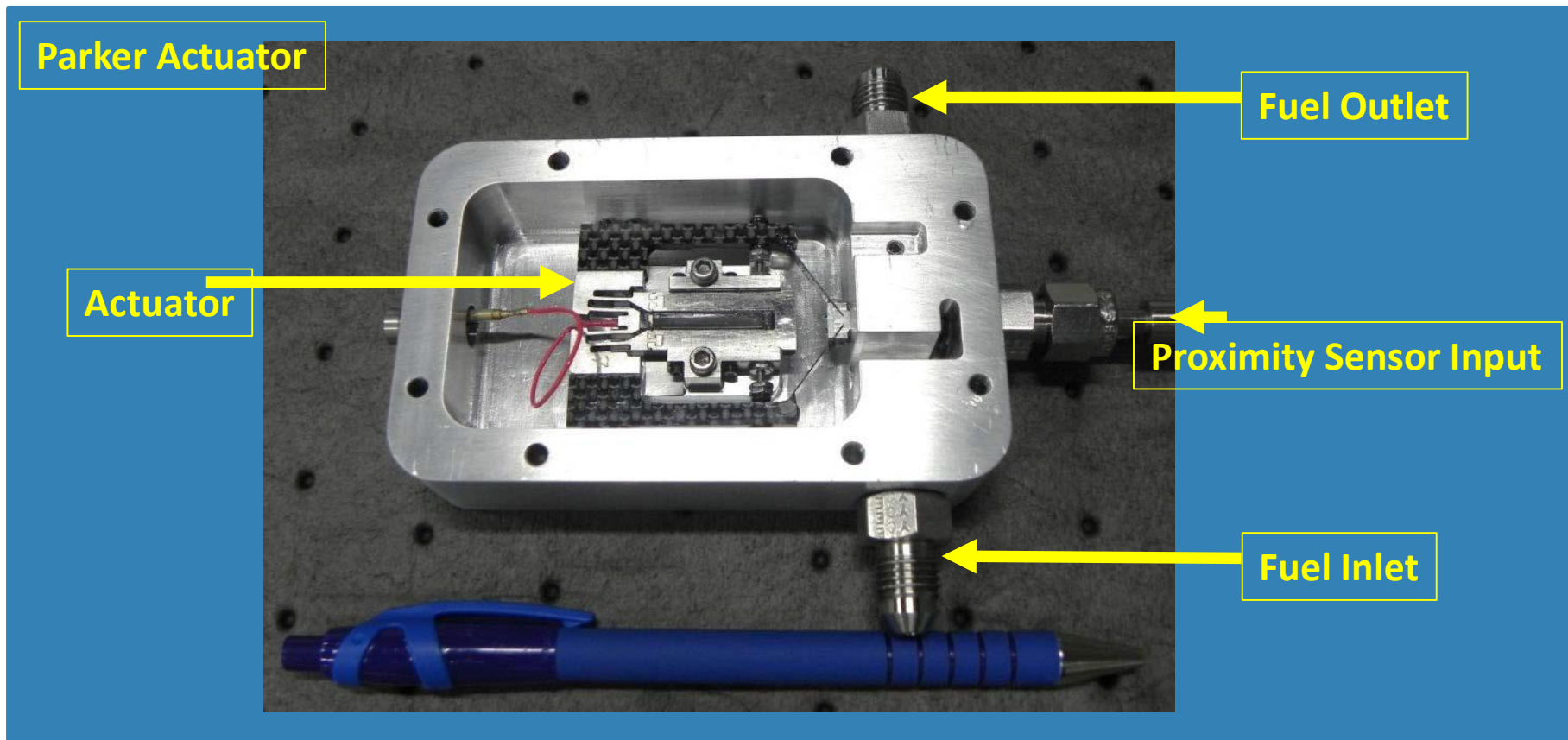
Envelope: 2"x4.5"x1"
Weight: 1 lbs

Max Power In: 6 amps
Max Pressure In: 1500 psi
Max Temp.: 300 °F

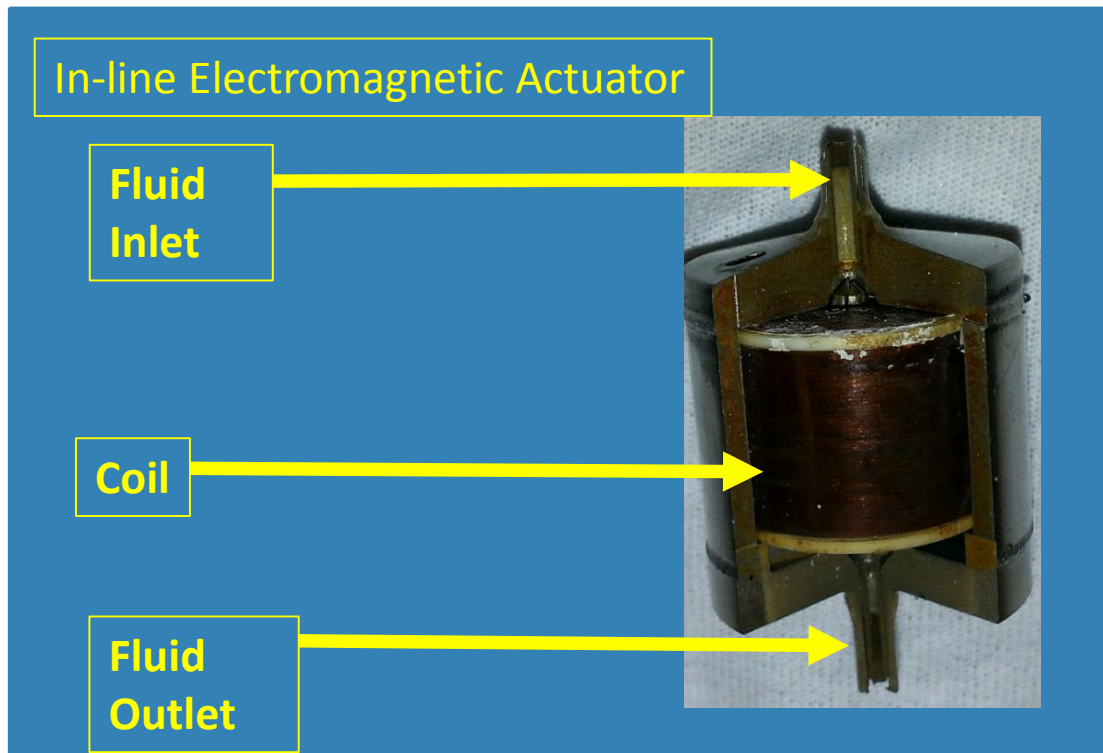
Max Power In: 6 amps
Max Pressure In: 1500 psi
Max Temp.: 300 °F

Max Power In: 6 amps
Max Pressure In: 1500 psi
Max Temp.: 300 °F

Max Power In: 1 amp
Max Press. In : 1500 psi
Max Temp.: 1800 °F

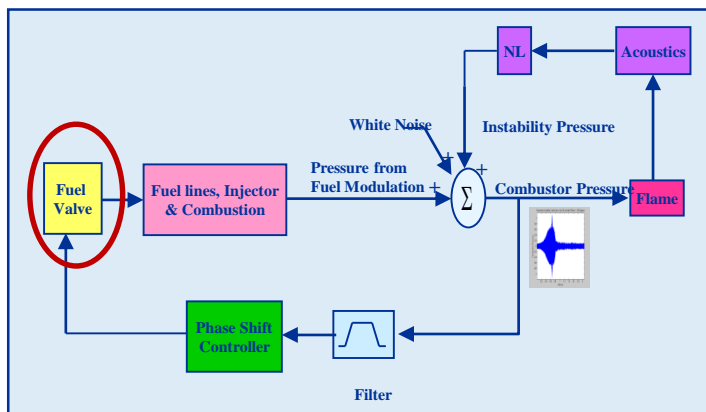


- Piezo Electric Actuator
- Fuel Flow Device
- $FN_{(nominal)} \approx 3.0$
- $Bw \approx 1K\ Hz$

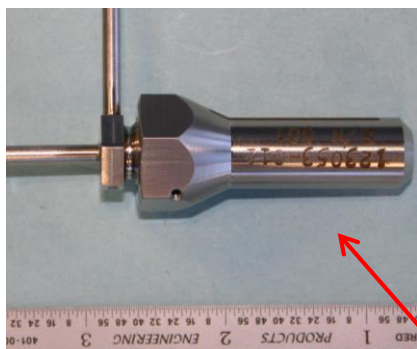


- **Electro-magnetic Actuator**
- **Fuel and Water Flow Device**
- $FN_{(nominal)} \approx 5.0$
- $Bw \approx 100 \text{ Hz}$

Active Combustion Control - Fuel Modulator Development



High Bandwidth fuel flow modulation is essential for suppression of thermo-acoustic instabilities



Active Signal Technologies, Inc., Fuel-Flow Modulator

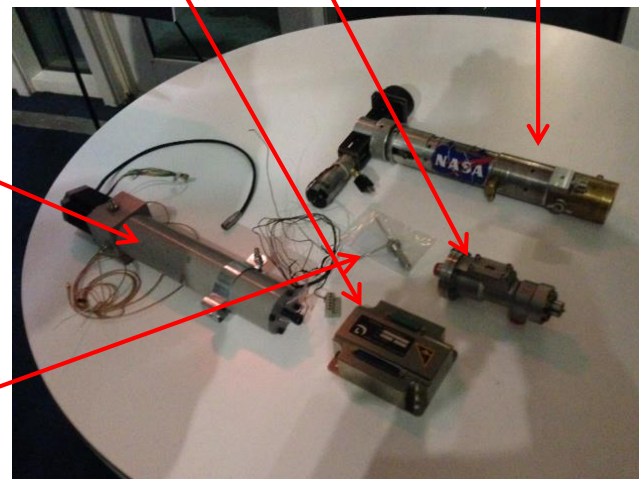
WASK Engineering, Inc. SBIR Phase I Prototype Model Fuel-Flow Modulator

JASC Device Drive Electronics



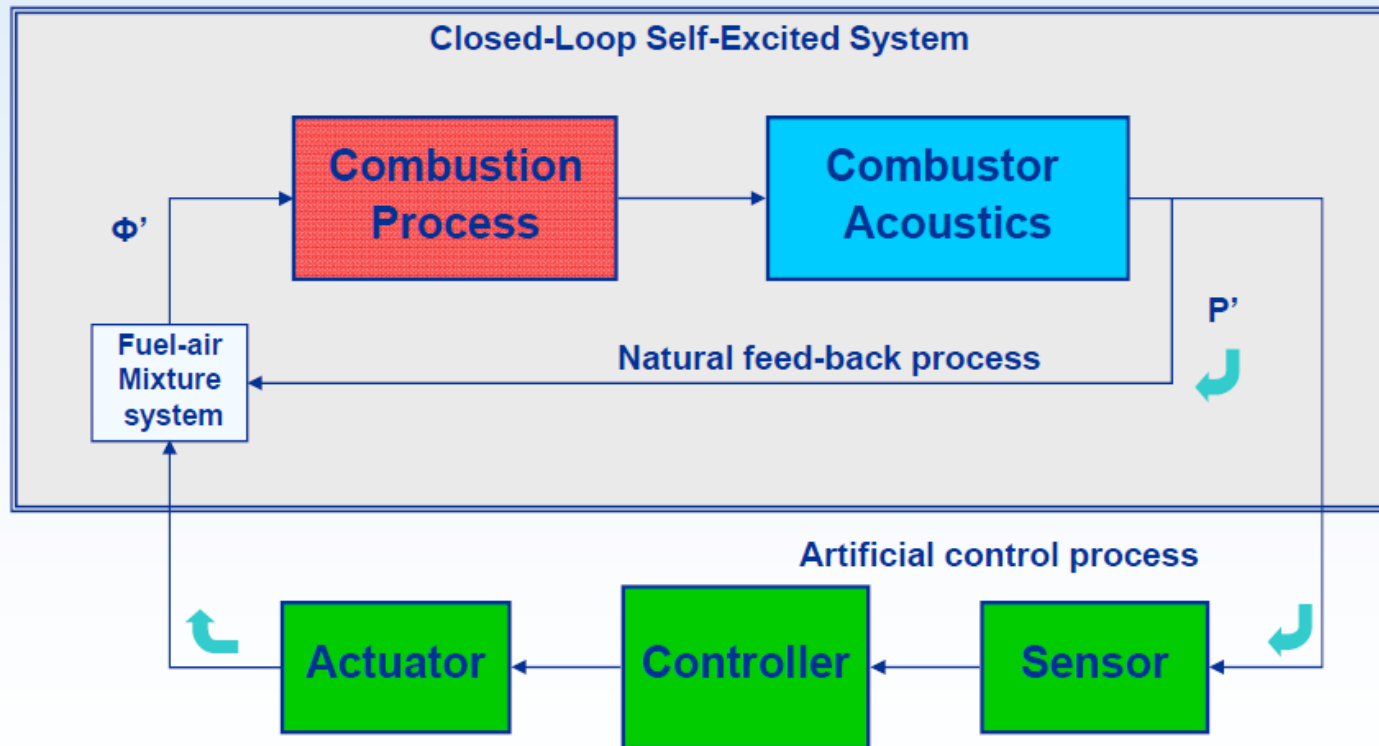
Jansen Aircraft Systems Controls, Inc. (JASC) SBIR Phase II Fuel-Flow Modulator

Georgia Tech Fuel-Flow Modulator

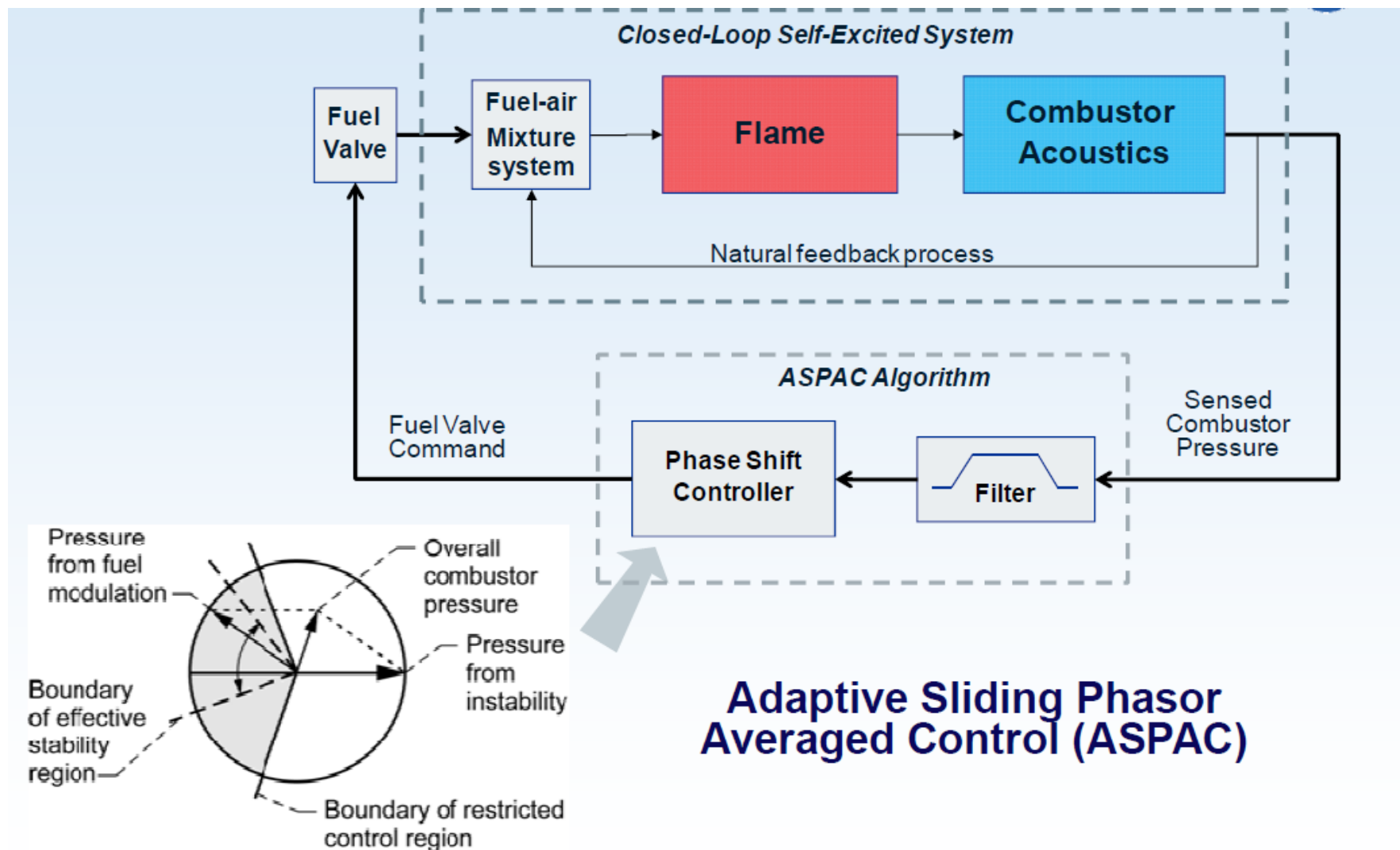


Active Combustion Control Loop

Objective: Suppress combustion thermo-acoustic instabilities when they occur



Active Combustion Control Loop





Active Combustion Future Plans

Complete buildup of Fuel Flow Modulator Test Facilities:

- CE7a water circuit,
- aCE7a water circuit, and
- Mobile Characterization Platform fuel circuit.

Perform Open Loop Controls Testing In CE13c and CE5
Flame Tubes:

- JASC modulator 1QFY16,
- Okojie modulator 2QFY16, and
- Parker modulator 3QFY16.

Perform Closed Lop Control Testing in CE13c and CE5.



Summary

- Increase Efficiency,
- Decrease Bad Emissions.
- Thermo-Acoustic Instability
 - Challenge
 - Strategy
- Future Work
 - Sensor Development
 - Actuator Development
 - Control Algorithm Development



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- Le, D.K., DeLaat, J.C., and Chang, C.T., “**Control of Thermo-Acoustic Instabilities: The Multi-Scale Extended Kalman Approach**,” AIAA-2003-4934, July 2003.
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- Paxson, D.E., “**A Sectored-One-Dimensional Model for Simulating Combustion Instabilities in Premix Combustors**,” NASA TM-1999-209771, AIAA-2000-0313, January 2000.



Questions?